5.4.3 New Design of a Thin Metallic Beam Pipe

In the PD1 study, two types of thin metallic beam pipe (one water-cooled, another rigid rib-reinforced) have been examined but both were rejected. Instead the design called for an external vacuum skin on the main magnets with metallic liners inside the magnet aperture. In the PD2 study, however, a new type of beam pipe was investigated and found to be promising. [1,2] This is a thin metallic pipe reinforced by multi-layer spiral metallic ribs. The pipe is made of Inconel 718 with thickness of a few tenths of mm. Each spiral rib has a cross section of about 0.3 mm^2 and can be bonded to the pipe by using laser deposition technique (e.g., precision metal deposition, or PMD). [3] Compared with other designs (e.g., ceramic beam pipe with a metallic cage used in the ISIS at the RAL), this new pipe will reduce the magnet aperture significantly, which, in turn, reduces the construction and operating cost of a synchrotron.

The cross section of the proposed beam pipe is a 4-in by 6-in oval with a thickness of 8 mils. The material is Inconel 718. The laser precision metal deposition method will be used to put a spiral rib (same material with 18 mils height and 28 mils width can be applied repeatedly) around the tube to increase its strength against buckling. We select 10 layers of reinforcement (hence the total height of the rib is 0.18 inch) and the pitch of the rib is set to 1 inch. Some relevant material properties of Inconel 718 are: tension modulus $E = 29 \times 10^6$ psi, yield strength $\sigma_y = 171 \times 10^3$ psi, ultimate strength $\sigma_u = 196 \times 10^3$ psi, electric resistivity $\lambda = 125 \times 10^{-8}$ Ω-m.
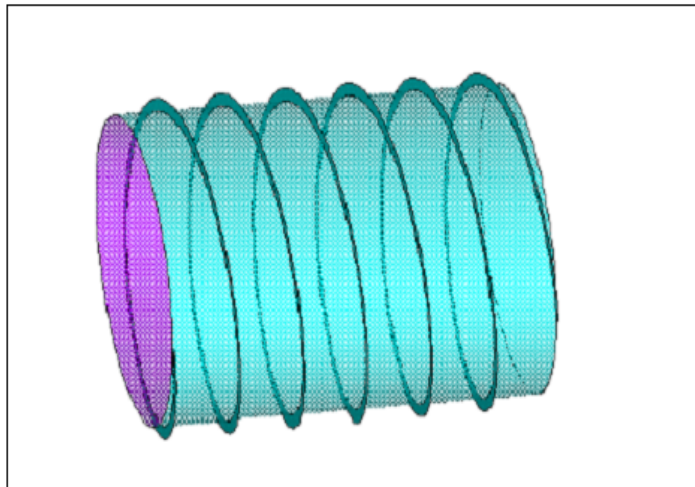

Figure 5.4.3. 1. Metallic beam pipe reinforced by spiral ribs

A finite element model is built for structural analysis. The only load considered here is the vacuum pressure of 14.5 psi. The effect of the electromagnetic force will be discussed separately.

Fig. 5.4.3.2 shows the equivalent stress of the pipe under vacuum. The maximum stress reaches 130 ksi. (Note: The stress on the edge is a bit higher. But that is due to the boundary condition used in the model and is not real.) According to the ASME pressure vessel code, the maximum allowable stress is 170 ksi. So this should be fine.

Fig. 5.4.3.3 shows the deformation of the beam pipe under vacuum. (The reinforcing ribs are not shown in this plot.) The major radius extends by 0.055 inch (1.40 mm), and the minor radius shrinks by 0.089 inch (2.26 mm).
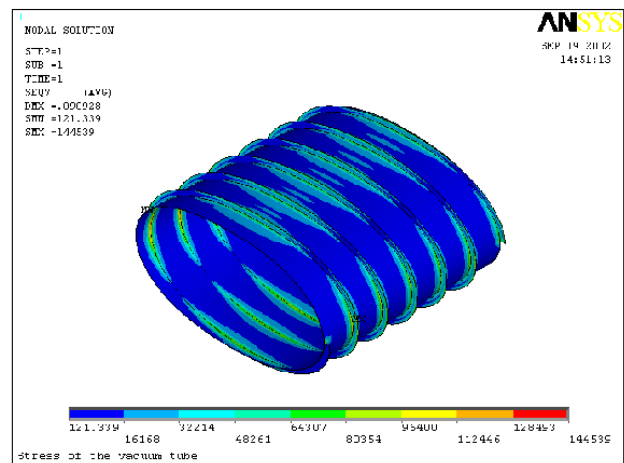

Figure 5.4.3. 2. FEA structural model, stress plot

So the deformation is not small. To achieve the required pipe dimensions under vacuum, the pipe should be pre-formed with smaller major radius and larger minor radius.

Since the beam pipe is made of metal, the time varying external magnetic field will induce eddy currents. These eddy currents will have several effects: distorting the external field, causing power loss and adding an electromagnetic pressure. The external field is dual harmonic. It resonates at 15 Hz with 12.5% 30 Hz component. The maximum field strength is 1.5 T, and the minimum 0.2 T.
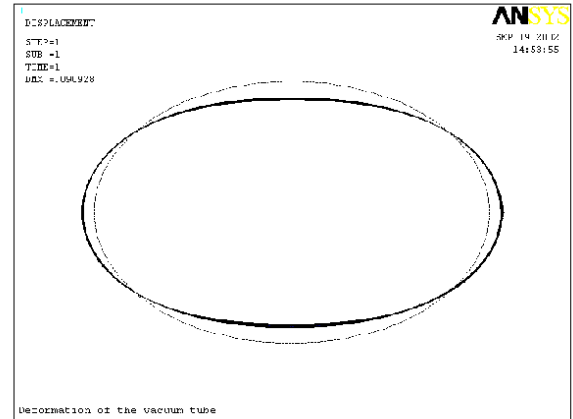
Figure 5.4.3. 3. Deformation of the beam pipe

For a single spiral rib, symmetry considerations lead to the conclusion that the eddy current caused by the spiral rib is negligible when compared with the beam pipe itself. Both analytical and finite element methods are used to analyze the eddy current effects. Results are summarized as follows.

For 15 Hz field, calculated power loss is 308 w/m; for 30 Hz field, power loss is 19 w/m. So the total power loss should be 327 w/m. This number compares well with the analytical result, which is 323 w/m.

Consider the magnetic field inside the vacuum tube on mid plane. The results show that the magnitudes are almost exactly the same as that of the applied external fields, and the lag angles are extremely small. That is to say, the magnetic field distortion due to eddy current is extremely small. Therefore, no correction will be needed. The analytic results are: the ratio of magnetic field induced by the eddy current to the external field is 0.613×10^{-3} for 15 Hz field and 1.227×10^{-3} for 30 Hz field.

The electromagnetic force is calculated analytically. It is a time changing quantity. We integrate the total force acting on $x > 0$ half beam pipe

$$F = 1.462 \, B \, \dot{B}$$

The maximum value of this function is 110 N/m. Compare this with the total force caused by the vacuum pressure, which is 10157 N/m. The former is about 1% of the latter. Therefore when we did the structural analysis by neglecting the magnetic force, the error was about 1%.

From this primary study, the proposed beam pipe should work. However, problems could occur during the manufacturing process. Some imperfections would be introduced. Certain damage to the tube material would be unavoidable. The strength of the beam pipe would depend on the perfection of the manufacture techniques. Therefore, prototyping of this beam pipe is an important R&D issue.

References

[1] Z. Tang, "A New Kind of Vacuum Tube for Proton Driver," FERMILAB-TM-2188 (2002).
[2] Z. Tang, W. Chou and A. Chen, "A New Kind of Beam Pipe for Rapid Cycling Synchrotrons," Proc. PAC 2003, May 12-16, 2003, Portland, Oregon, U.S.A.
[3] J. Rabinovich, H&R Technology Inc., Lowell, MA., private communication